Core Team Discussion Paper: Use of Conceptual Models in decision-making and directing investigations

Restoration or rehabilitation programs for complex ecosystems must be based on clear concepts about how the system is believed to work, how it has been altered or degraded, and how various actions might improve conditions in the system. This section presents an example in which conceptual models of various parts of the San Francisco estuarine ecosystem are used to explore various management alternatives and various needs for research and monitoring.

For this example we examine the effects of freshwater flow and exports on various species of interest. In particular we focus on the "Fish-X2" relationships (Jassby et al. 1995), by which abundance or survival of several estuarine and anadromous species is related to X2, the distance up the axis of the estuary to where daily average near-bottom salinity is 2 practical salinity units (psu). This index is useful in encapsulating the physical response of the estuary to freshwater flow.

The models presented here are more or less hierarchical: first we present an extremely simple landscape-level model, followed by an ecosystem-level model, and several models of specific processes. The models are used to explore issues to do with entrainment in the state and federal pumping facilities, and a potential mechanism by which increasing flow could cause some species to increase in abundance.

We do not assert that these models are the best possible representations of the processes being considered. Rather, we present them as an illustration of how they can be used. At the end of this section we present steps required to carry out the activities suggested here.

Landscape-level model

This is a very simple and straightforward model, presented only in words. Species being addressed in this section include chinook salmon and striped bass, both anadromous fish, and several species that spawn in the coastal ocean and rear in the estuary. These species link the system across boundaries, either between the rivers and the estuary, or between the estuary and the ocean. They do so by migrating, and in doing so they expose themselves to environmental conditions in each region. The principal landscape-level issue is to what extent the conditions in each region affect their abundance. For example, chinook salmon experience rigorous conditions in their spawning regions, during migration through the Delta, and in the ocean. If the Delta causes a substantial fraction of their mortality, the opportunity exists for restoration that will be effective in reducing mortality and increasing salmon production. Similar issues exist for the other species, although the lack of direct human influence on oceanic conditions (except harvest) limit the opportunities for restoration in that region.

Ecosystem-level model

The principal issue here is what mechanisms underlie the Fish-X2 relationships. We present first a very simple diagram (Figure 1) to illustrate the diverse mechanisms that could be in operation for different species. Briefly, the relationships could arise (as similar ones do in

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estuaries in other parts of the world) as a result of stimulation of growth at the bottom of the food chain, which then propagates upward eventually to fish. On the other hand, there is good evidence from this estuary (Kimmerer 1998) that direct physical effects on fish are more likely. These effects occur through two general classes of mechanisms. First, flow conditions in the estuary set up by tides and freshwater input, and in some cases by export flows, may alter the degree of retention within the estuary, thereby affecting population size. Second, the extent of physical habitat may change with freshwater flow through such effects as inundation of flood plains or expansion of low-salinity shallow habitat.

To provide further detail on the ecosystem-level model we use part of the Estuarine Ecology Team's report on the "Fish-X2" relationships (EET 1997). That report included a matrix (Figure 2) that summarized knowledge on each of the potential mechanisms underlying the observed relationships. For each mechanism and each species, a symbol was used to denote the importance of that mechanism to that species, and the degree of certainty/uncertainty associated with that mechanism and species. Although the intent of this matrix was to develop research proposals, it can also be used for examining various alternative causes for variation in abundance with flow.

The symbols used (Figure 1) are large and dark for mechanisms that are believed to be important but for which there is little information. Large, open circles denote important mechanisms for which at least some, possibly qualitative, information exists. A distinction was made between mechanisms that operate in the estuary and those that operate entirely upstream, such as variation in spawning habitat for salmon. These upstream mechanisms were included for completeness but were not discussed in any detail.

Each of the mechanisms has a precise definition (EET 1997), but we consider here only a few of them. First, examine the row labeled "Reduced entrainment (CVP-SWP)". There are 5 large open symbols and a number of smaller symbols. Large symbols are given for all of the anadromous species included in the matrix except for splittail. Thus, the EET believed that for these 5 species, entrainment could explain at least part of the observed X2 relationship, and this relationship was reasonably well-understood.

Now examine the row labeled "gravitational circulation strength". There are 6 large filled circles, including species that recruit from the ocean as well as several that move down-estuary during development and then reside mainly in Suisun or San Pablo Bays and the Delta. Similarly, several issues relate to habitat, of which "rearing habitat space" was considered an important probable mechanism for the largest number of species, although knowledge of this topic is limited.

In succeeding sections we add detail in developing conceptual models of these mechanisms, and discuss their consequences.

Conceptual model of entrainment

We present two alternative conceptual models of how anadromous fish can be entrained in the state and federal water projects under low-flow conditions (Figure 3). The upper part of the figure shows schematic maps of the Delta with the key nodes identified at which water and anadromous species diverge into separate pathways. Conceptual model A is the "old" model,

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in which the emphasis is on net flow. Water moves downstream in the rivers, and either toward the ocean or toward the pumps in the Delta, including a landward net flow in the lower San Joaquin River ("QWEST").

Conceptual model B is based on more recent developments in understanding of hydrodynamics of the Delta, and the realization that fish are not passive particles but are capable of quite complex behavior. Flow in the rivers is downstream, but as we move into the Delta the flow becomes increasingly dominated by tides. The further west in the Delta we go, the more important the tides are and the less important is river flow in terms of instantaneous velocity. For example, at Chipps Island under low-flow conditions net flow is only 1-2% of tidal flow.

The bottom panel in Figure 3 illustrates what factors influence the proportions of fish that take one course or another at each of the numbered nodes in the upper panel. Starting from the left-most bar chart, according to conceptual model A, striped bass larvae are largely subject to net flow, with tides affecting them to some degree at the confluence of the rivers (Node 3). Salmon smolts, by contrast, are affected more by their own behavior. Still, the major influence is net (river) flow.

Under conceptual model B, striped bass larvae are affected mainly by tidal flows, and to a lesser extent by net flows. Furthermore, the influence of net flows is nearly gone by the time the larvae reach the confluence (i.e., the Low-Salinity Zone, which under low-flow conditions in spring is at about the confluence). Behavior of the larvae is non-negligible in this model, particularly when they reach brackish water and begin to migrate vertically.

Salmon smolts are mostly governed by their own behavior, particularly that aspect of it that determines whether they migrate along the shore or across the river. If the former, they are more vulnerable to diversions such as at the Delta Cross-Channel than if they are distributed across the channel. In addition, at the more landward nodes it is tidal, rather than net flow, that has the most influence on their movement patterns. This is because we assume that, like all other organisms living in tidal environments, they are exquisitely sensitive to the tidal movements and phasing, and are capable of moving downstream rapidly using the tidal currents. Thus, their movement is governed by an interaction between their behavior and the tide.

These alternative models make radically different predictions about the effect of entrainment on these species and the most effective measures to minimize the effects of entrainment (Table 1). According to Model A, losses can be minimized by reducing exports and maximizing flow, and moving the intake up into the Sacramento River would have a clear benefit. Model B, on the other hand, suggest that export flows are not very important in killing salmon, and that the most important issue is the strength of the environmental cues available to guide the salmon to sea. Note that this model is more consistent with recent statistical modeling results, which do not support an important role of variation in export flow in explaining variation in salmon smolt survival.

For striped bass, the predictions of Model A are again that net flows are important and that increasing flow and reducing exports would benefit striped bass. Model B, on the other hand, posits a probability of entrainment that depends on the initial position of the fish and the strength of tidal and net flows including export flows. The further seaward the fish is at first, the

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less likely it is to be entrained. Moving the salt field seaward (i.e., moving X2 seaward) reduces the exposure of the fish to entrainment, and is therefore more effective than curtailing exports. Note the sharp contrast in predictions of the two models of effects of moving the intake site.

For Delta smelt, the picture is a bit less clear. Under model A, minimizing exports is very important, and moving the intake facility would be very helpful for Delta smelt. The export:inflow ratio can be used to scale exports to the available water; minimizing that ratio is believed to reduce the proportion of the smelt population that is entrained. Model B works similarly to the model for striped bass, in that X2 determines the position of the bulk of the population and therefore the exposure to entrainment, while variation in export flow has little effect unless X2 is landward. Thus moving the intake facility would have little effect except under very low-flow conditions.

These results suggest a need for an adaptive-management approach to determining the effects of entrainment. Although this is being attempted in the Vernalis Adaptive Management Program, and has been suggested for flow conditions during seaward migration of spring run salmon, active adaptive management could be greatly expanded to attempt to resolve this key issue.

Alternative models for X2 effects

Here we contrast two mechanisms that are believed to be important for species that enter the estuary from the ocean as young, or spawn in the lower bays and rear in the estuary. These mechanisms are gravitational circulation and extent of physical habitat for rearing.

Recent developments in understanding of the physical characteristics of the estuary have altered our perception of how the biota use their environment (e.g., Burau 1998). Figure 4 illustrates a conceptual model of estuarine circulation patterns designed to illustrate these concepts. For the purposes of this exercise, the main points are as follows. First, flow within the brackish parts of the estuary can be considered to have three components as illustrated. First, there must be a cross-sectionally averaged residual (i.e., averaged over the tides) flow to seaward that is equal to the river flow. Second, vertical and lateral asymmetries in residual flow occur through the interaction between stratification, tides, and bathymetry. Third, the strongest flows in most of the are reversing tidal flows which induce strong longitudinal and lateral dispersion.

Freshwater flow introduces a pressure or level gradient that makes water want to go seaward through the estuary. At the same time, tides drive the denser ocean water into the estuary through a combine pressure and density gradient. These opposite forcings determine the length of the salinity gradient and therefore the density gradient. High freshwater flow over a period of time compresses the longitudinal density gradient, enhancing stratification and possibly gravitational circulation.

Gravitational circulation (Figure 5) can occur throughout the estuary if stratification occurs. This happens primarily in deep regions such as the Golden Gate, the main channel through Central and San Pablo Bays, and in Carquinez Strait. It is rare in the main channel of Suisun Bay (Burau 1998). We assume (because this theory has not been tested) that stratification is stronger when freshwater input is high, because of the compression of the longitudinal density gradient (Figure 4). Under low-flow conditions (Figure 5 top) stratification is slight. Near-bottom currents are smaller than near-surface currents and slightly stronger on the ebb than on the flood near surface, and on the flood than the ebb near-bottom.

When flow is high, stratification is stronger and the longitudinal density gradient is steeper, causing an intensification of gravitational circulation: the ebb-flood asymmetry in near-bottom currents in particular is greater.

Certain species of bay residents may use gravitational circulation to enter the estuary and to move landward; this is a common mode of transport for flatfish larvae and shrimp (). Essentially all they need to do is move downward and gravitational circulation will take them landward. Presumably the stronger the gravitational flow the more rapid the movement, and the larger the abundance of animals that will arrive at the rearing habitat. If correct, this model could explain the X2 relationships for bay shrimp, starry flounder, and possibly Pacific herring.

The alternative model holds that the physical extent of nursery habitat increases with increasing flow. This model is supported by a preliminary analysis of the area in the estuary encompassed by selected salinity values (Unger 19xx). If habitat is limiting the development of these populations, and if it does indeed increase with flow (at least over some range), then this too could explain the observed relationships.

Actions to protect and enhance the abundance of these species (and the predatory species that depend on them) differ depending on which mechanism is most important. If the major mechanism is gravitational circulation, there is little that can be done to enhance these populations other than to increase freshwater flow (note that dredging channels may also accomplish this but an additional result may be greater salt penetration). However, if limiting habitat is the key issue, then it may be possible to provide more, better, or more accessible habitat, and achieve a suitable level of protection or enhancement with considerably less flow.

Next steps

A substantial number of issues need to be explored so that appropriate restoration actions can be selected. We suggest the following method to characterize key issues and to develop actions that can resolve them.

1. *Identify the major issues surrounding potential restoration actions.* These issues should not be hard to identify, most of them having been contentious for a long time.

2. *Identify and brief 5-7 key people involved with each issue.* These people should be experts in their field, with perhaps 1-2 from other estuary/river systems. The team members would meet for an initial briefing with a broader group including stakeholder and agency representatives, and with alternative viewpoints presented.

3. *Conduct workshops on the key issues.* The team would then meet privately once or more, with some opportunity for analysis between meetings. Brief reports would be prepared after workshops to apprise stakeholders and agencies of progress.

4. *Hold public workshop(s) to present findings.* These workshops would be used to disseminate findings and recommendations, and to provide review and feedback.

5. *Develop report and conduct peer review.* The team would then prepare a report which would be sent to two or more anonymous reviewers.

6. *Finalize report and recommendations.* The final reports should clearly articulate the issues, describe the methods used, the resolution attained, and any dissenting points of view. It should recommend actions to take, adaptive management to be instituted, and monitoring or research that are needed.

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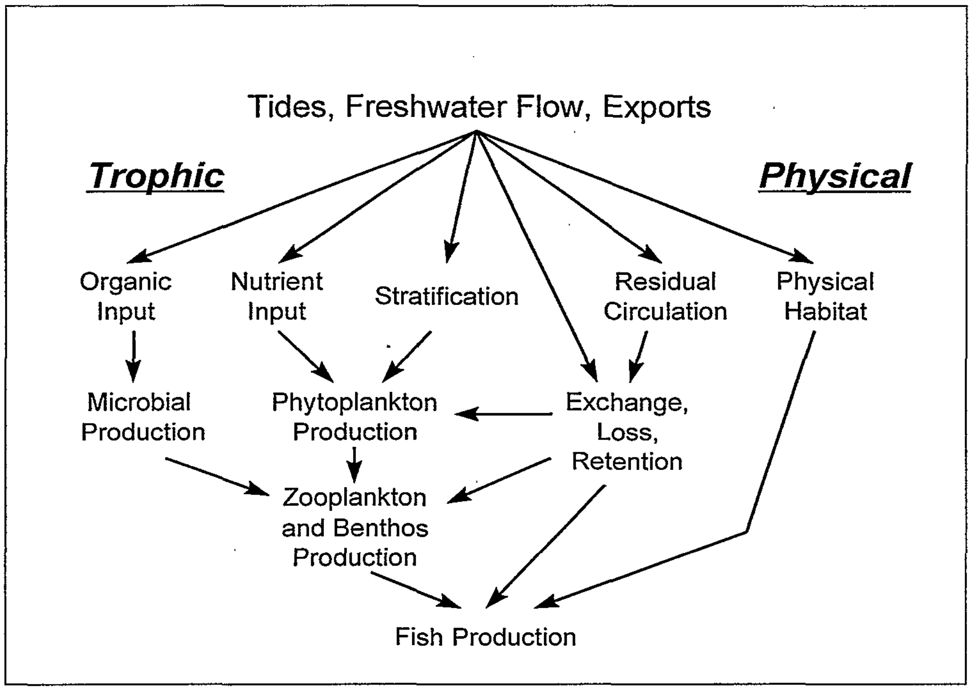

Figure 1. Schematic diagram showing potential causative pathways underlying the "Fish-X2" relationships. The labels "trophic" and "physical" indicate that causative pathways to the left of the diagram are more biological, based on feeding relationships, while those on the right describe mechanisms that arise through interactions with physical conditions and abundances of species of interest. Tides, freshwater flow, and exports influence organic and nutrient inputs, stratification and gravitational circulation, and the extent of physical habitat with various characteristics. Organic and nutrient input can stimulate growth at the bottom of the food web, which may progress to higher trophic levels such as fish. Export flow together with residual and tidal circulation within the estuary may interact with behavior to affect losses from the estuary or, alternatively, retention. Thus fish may benefit from increased flow through increased food supply, improved retention within their habitat, or an increase in the quantity or availability of physical habitat.

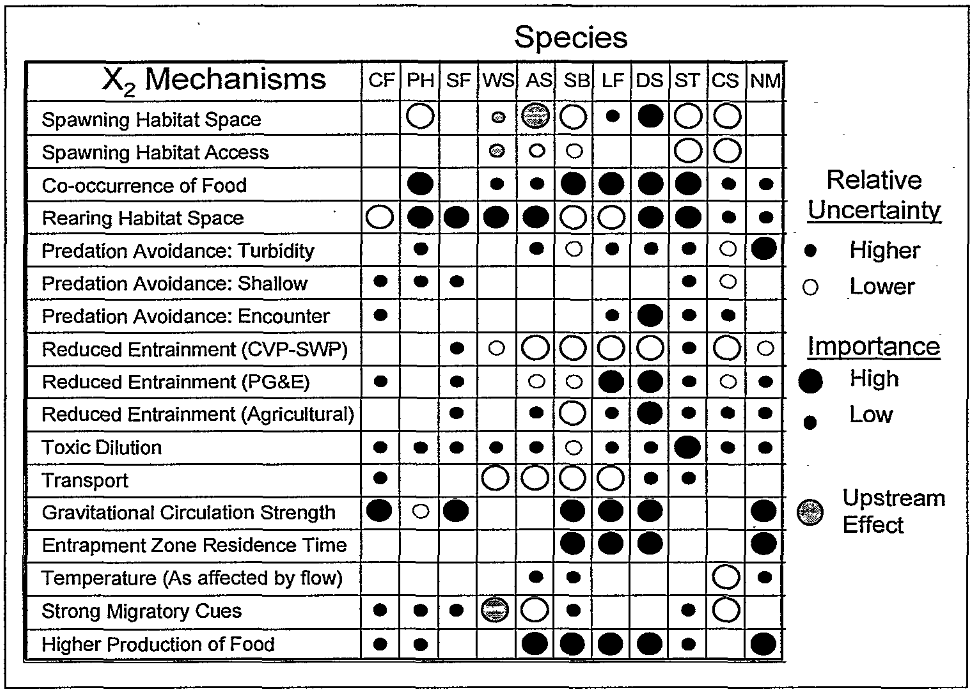

Figure 2. Estuarine Ecology Team's summary of potential causes underlying "fish-X2" relationships, with symbols indicating a potential mechanism according to the key at right. Several minor mechanisms have been eliminated to simplify the diagram. "Upstream" effects refer to flow effects that occur entirely upstream of the Delta. Species are:

CF	Bay shrimp, *Crangon franciscorum*
PH	Pacific herring
SF	Starry flounder
WS	White sturgeon
AS	American shad
SB	Striped bass
LF	Longfin smelt
DS	Delta smelt
ST	Splittail
CS	Chinook salmon (note: few major effect are in the delta)
NM	*Neomysis* and other mysids

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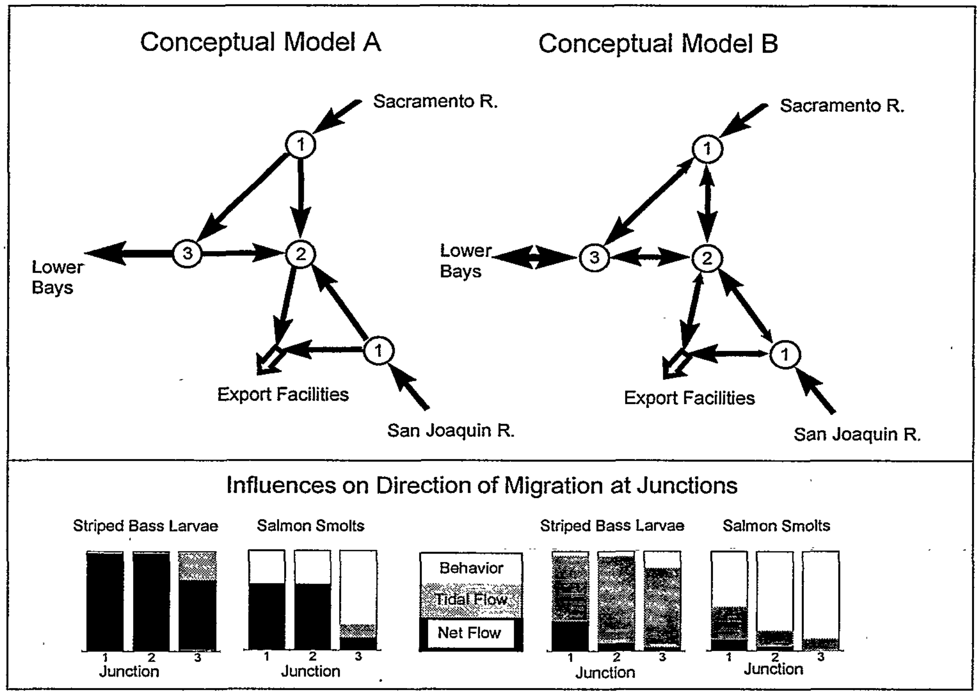

Figure 3. Alternative conceptual models of flow and fish movement in the Delta under low-flow, high-export conditions. Arrows and circles comprise a schematic of the Delta, with the circles representing key nodes where flow and fish diverge. Single arrows indicate river inputs, and double arrows indicate flows that are partly or mostly tidal, with the sizes of the arrowheads reflecting relative flow velocities for each location. Conceptual model A depicts net flows, with arrows indicating how fish would move under the influence of these flows. Conceptual model B illustrates how water moves in response to both tides and net flow. Fish move under the influence of these flows and their own behavior. Bar charts in the bottom panel illustrate how these conceptual models differ in their prediction of the relative influence of fish behavior, tidal flow, and net flow on the proportion of fish taking alternative pathways at each of the nodes.

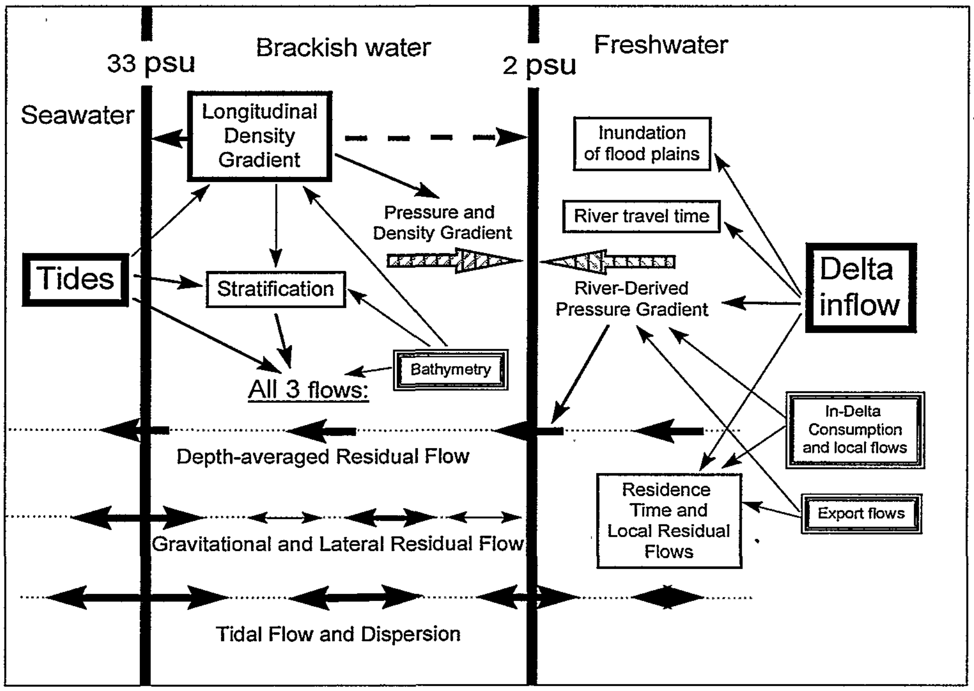

Figure 4. Conceptual model of flow effects with emphasis on the brackish parts of the estuary. Freshwater inflow and tides are the major forcing functions. The principal role of freshwater input is in setting up a pressure (level) gradient along the axis of the estuary, which forces the depth-averaged residual flow throughout the estuary. Tides introduce a pressure gradient that varies in time, and the salinity gradient due to tidal mixing between fresh and salt water sets up a density gradient. This interacts with tidal mixing and bathymetry to produce various degrees of stratification and gravitational circulation.

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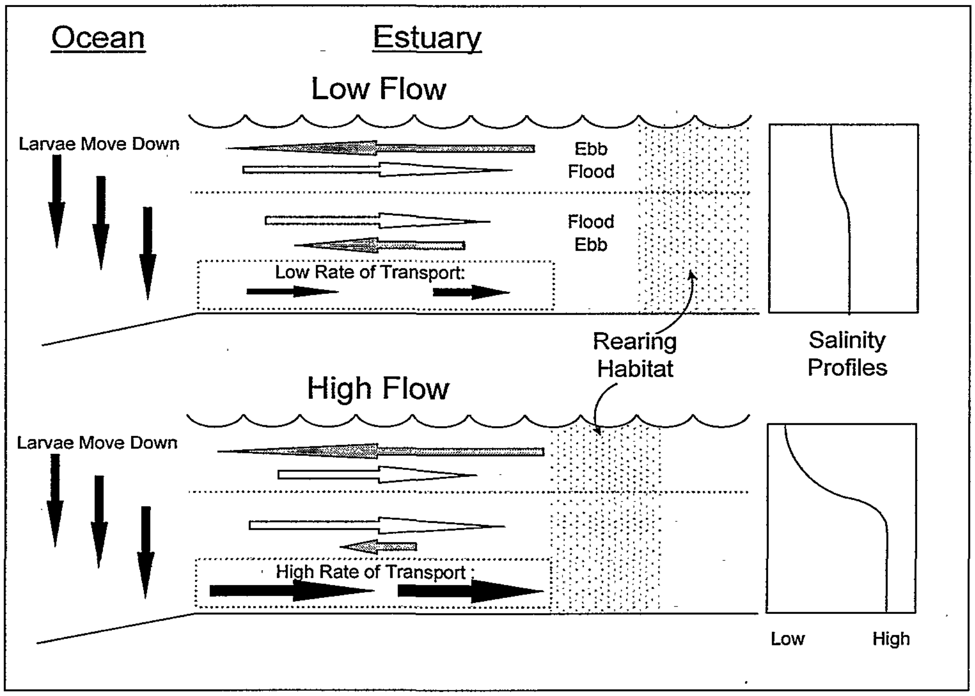

Figure 5. Conceptual model of the mechanism for the X2 effect based on gravitational circulation. Several species recruit from outside the estuary and must enter the bay to reach nursery areas; some other species reproduce within the bay but then move up the estuary for rearing. Tidal flows in the low-salinity and high-salinity layers are shown as arrows , with gray representing ebb and white representing flood. Black arrows indicate larval movement. Under low-flow conditions, stratification and gravitational circulation are weak; landward transport of larvae is slow. High flow compresses the longitudinal density gradient (Figure 3), increasing stratification and gravitational circulation, and increasing the rate of larval transport. Note that this model has not been tested.

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Table 1. Comparison of conclusions for protection of selected species based on the choice of underlying conceptual model. This ignores effects of Delta Cross-channel gate positions and presence of the Head of Old River barrier.

Variable	Model A	Model B
Sacramento Salmon		
Proportion migrating into interior Delta	Flow splits based on Sacramento River flow	Tidal flows, some net flow effect, migratory behavior.
Proportion going to pumps	Flow splits in interior Delta, QWEST	Probability of entrainment based on behavior, ambiguous or incorrect cues, erroneous choices of migration route
Method to reduce losses	Minimize flow splits by maximizing flow and minimizing exports	Maximize seaward flow to provide clear cues; exports unimportant
Effect of moving intake facility	Large	Negligible
San Joaquin Salmon		
Proportion going down Old River from Mossdale	Flow splits based on San Joaquin River flow, export flow	Flow splits based on river and tidal flows, migratory behavior.
Proportion going up Old and Middle Rivers from lower San Joaquin	Flow splits in interior Delta, QWEST	Probability of entrainment based on behavior, ambiguous or incorrect cues, erroneous choices of migration route
Method to reduce losses	Minimize flow splits by maximizing flow and minimizing exports	Maximize seaward flow to provide clear cues;
Effect of moving intake facility	Very large	Moderate
Striped Bass		
Proportion of eggs and larvae going to pumps	Net flows	Probability of entrainment depends on net and tidal flows and export flow
Proportion of juveniles going to pumps	Net flows	X2 (position of Low-Salinity zone) establishes vulnerability, and export flows set up probability of entrainment
Method to reduce losses	Increase flow and reduce exports	Move X2 seaward ***or*** reduce exports
Effect of moving intake facility	Very large	Negligible
Delta smelt		
Proportion going to pumps	Export:Inflow ratio?	X2 establishes vulnerability, and export flows set up probability of entrainment
Method to reduce losses	Minimize exports	Move X2 seaward ***or*** reduce exports
Effect of moving intake facility	Very large	Large when X2 is landward

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